High Power FELs

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Newport News VA

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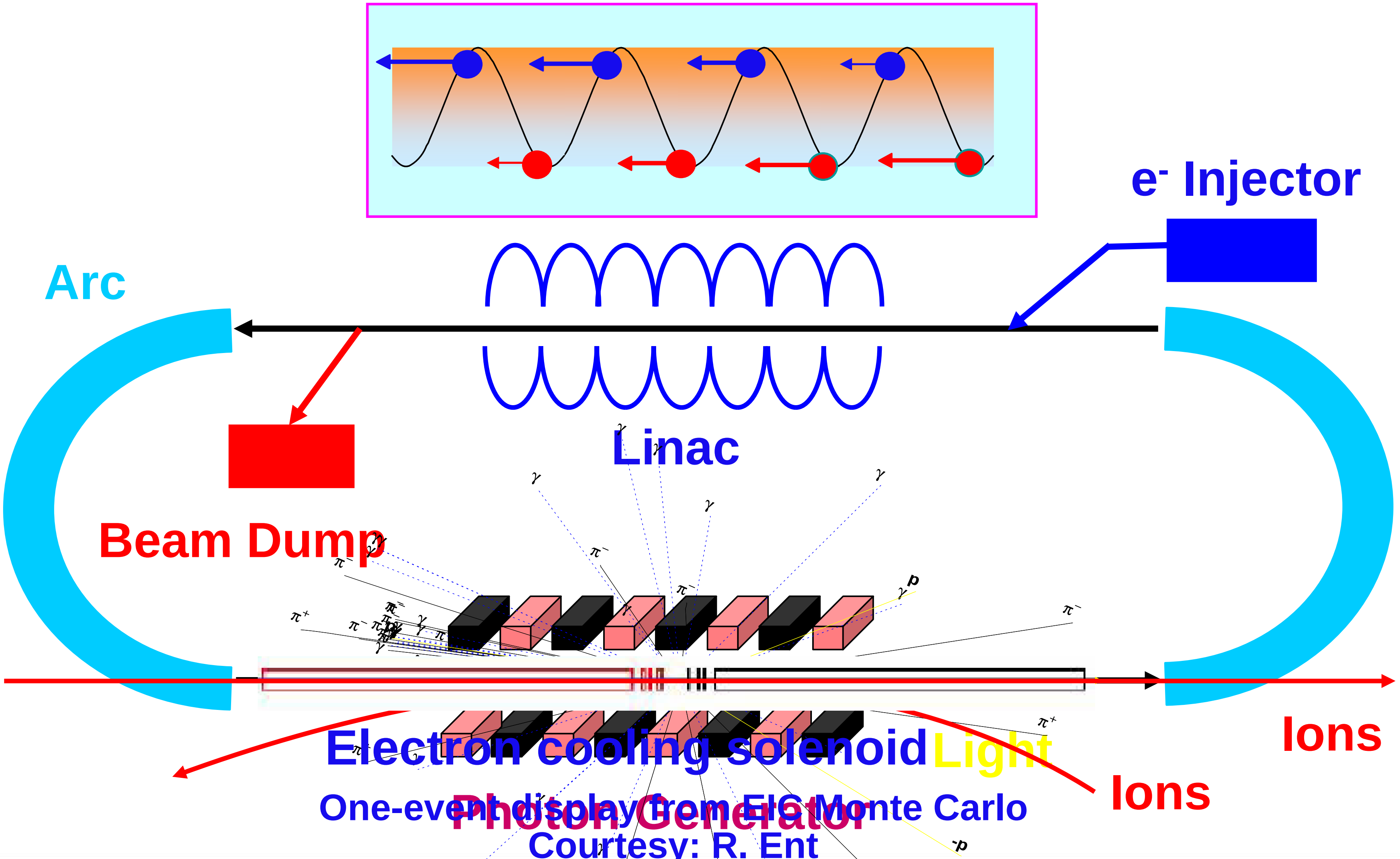
Outline

- Operating High Power FELs
  - Recuperator at Novosibirsk
  - JAEA Superconducting ERL
  - JLab IR Upgrade
- Test Stands, in commissioning
  - Daresbury ERLP
- Proposed
  - Daresbury 4GLS
  - KAERI FEL
  - Florida State University BigLight
- Supporting Technology Development
  - Injectors: srf guns, DC Gun
- Industrial Applications for FELs

High Power FEL ERLs

- ERL- A new form of linear accelerator where the energy is recycled rather than the electrons as in a storage ring forms the basis for the development of high power output
  - So far has only been done at <30 mA levels but it is believed that 100s of mA possible
  - ERL Benefits:
    - Reduced power consumption
    - Reduced rf required
    - Reduced power at the dump
    - Significantly reduced or eliminated neutron activation
    - Brighter light source beams

Energy Recovering Linacs



ERL vs. Storage Ring vs. Linac

- While an electron storage ring stores the same electrons for hours in an equilibrium state, an ERL stores the energy of the electrons.
- In an ERL electrons spend little time in the accelerator (~1 μs), therefore they never reach an equilibrium state.
- In common with linacs: In an ERL the 6-D beam phase space is largely determined by electron source properties which can be of significantly lower emittance in both dimensions and shorter in time than a storage ring equilibrium
- In common with storage rings: An ERL possesses high average current-carrying capability enabled by the ER process, thus promising high efficiencies.

ERL Light Sources Promise

High average

Why? Condensed matter studies move from X-ray statics to X-ray dynamics.

How do proteins work?

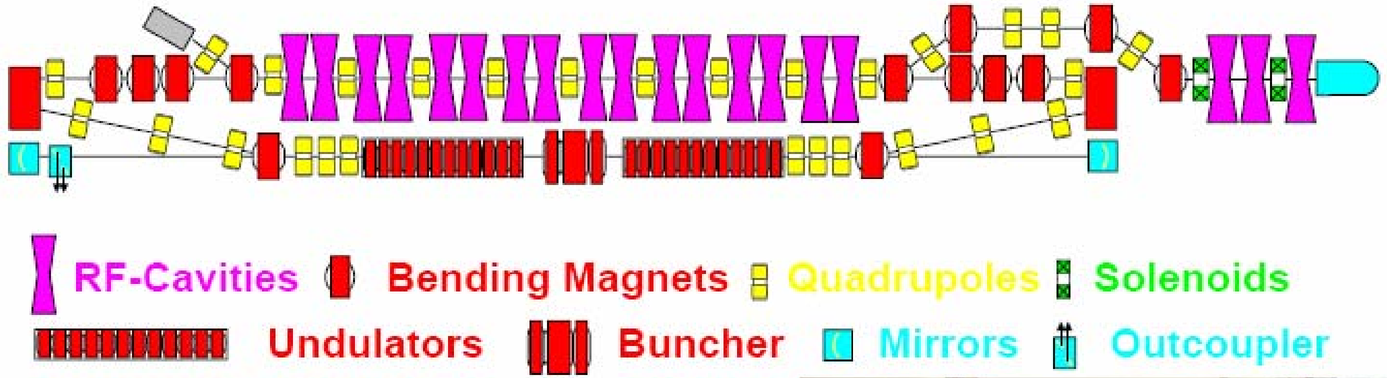
How are short range atomic correlations established and lost?

patterns

*quantities are rms

The Novosibirsk High Power THz FEL

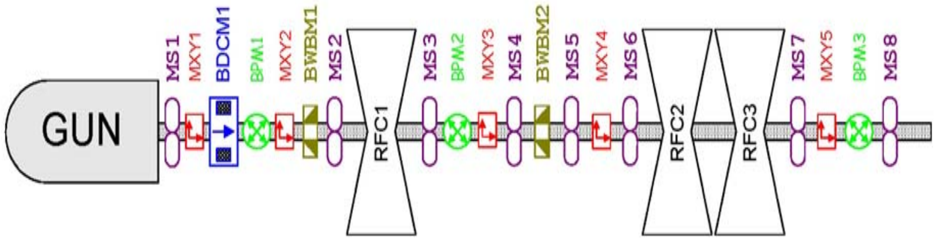
Energy recovered highest average current to date: 30 mA at 1.7 nC per bunch



	May 2005	Plans
RF frequency, MHz	180	180
Bunch repetition rate, MHz	**22.5!**	90
Maximum average current, mA	**30!**	150
Maximum electron energy, MeV	12	14
Normalized beam emittance, mm*mrad	30	15
Electron bunch length in FEL, ns	0.07	0.1
Peak current in FEL, A	10	20

Courtesy N. Vinokurov

Recuperator FEL Injector



MS : focusing solenoid

MXY : steering magnet

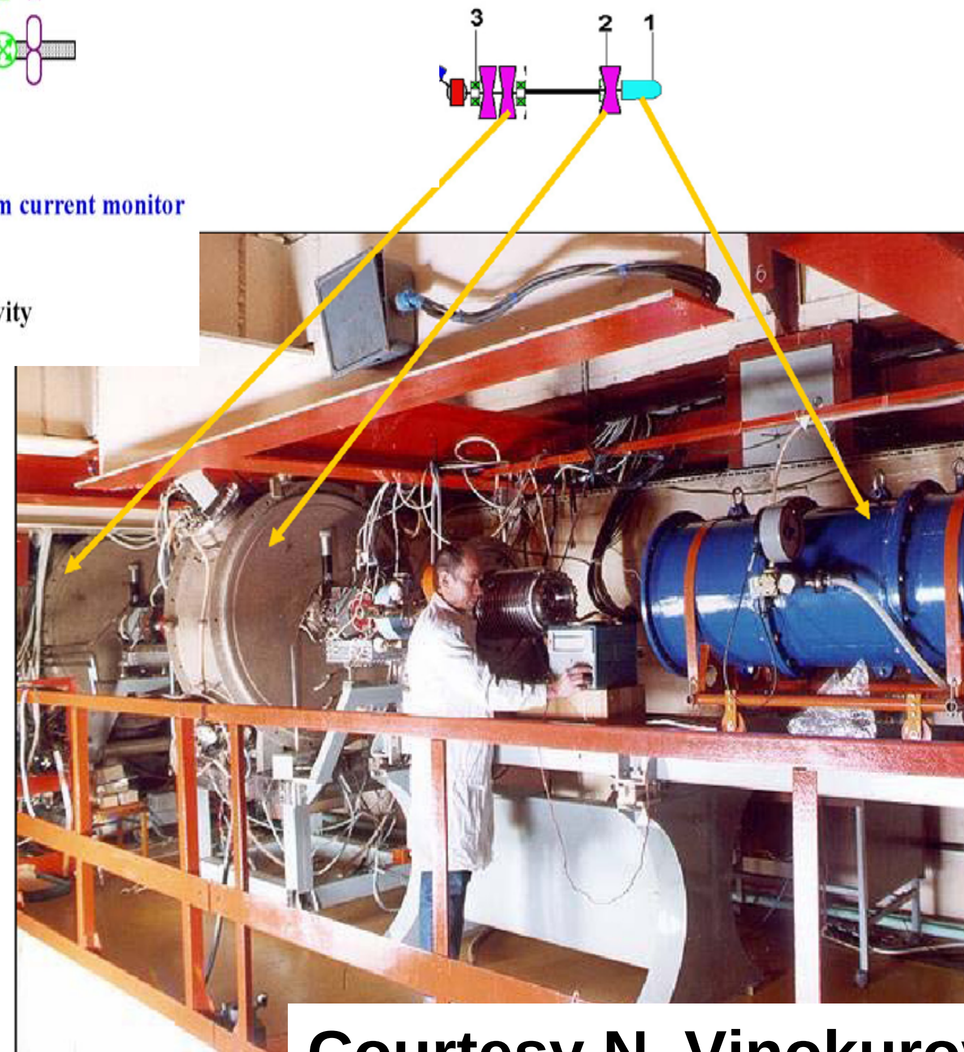
BDCM : beam current monitor

BPM : bean position monitor

BWBM : strip line monitor

RFC : RF cavity

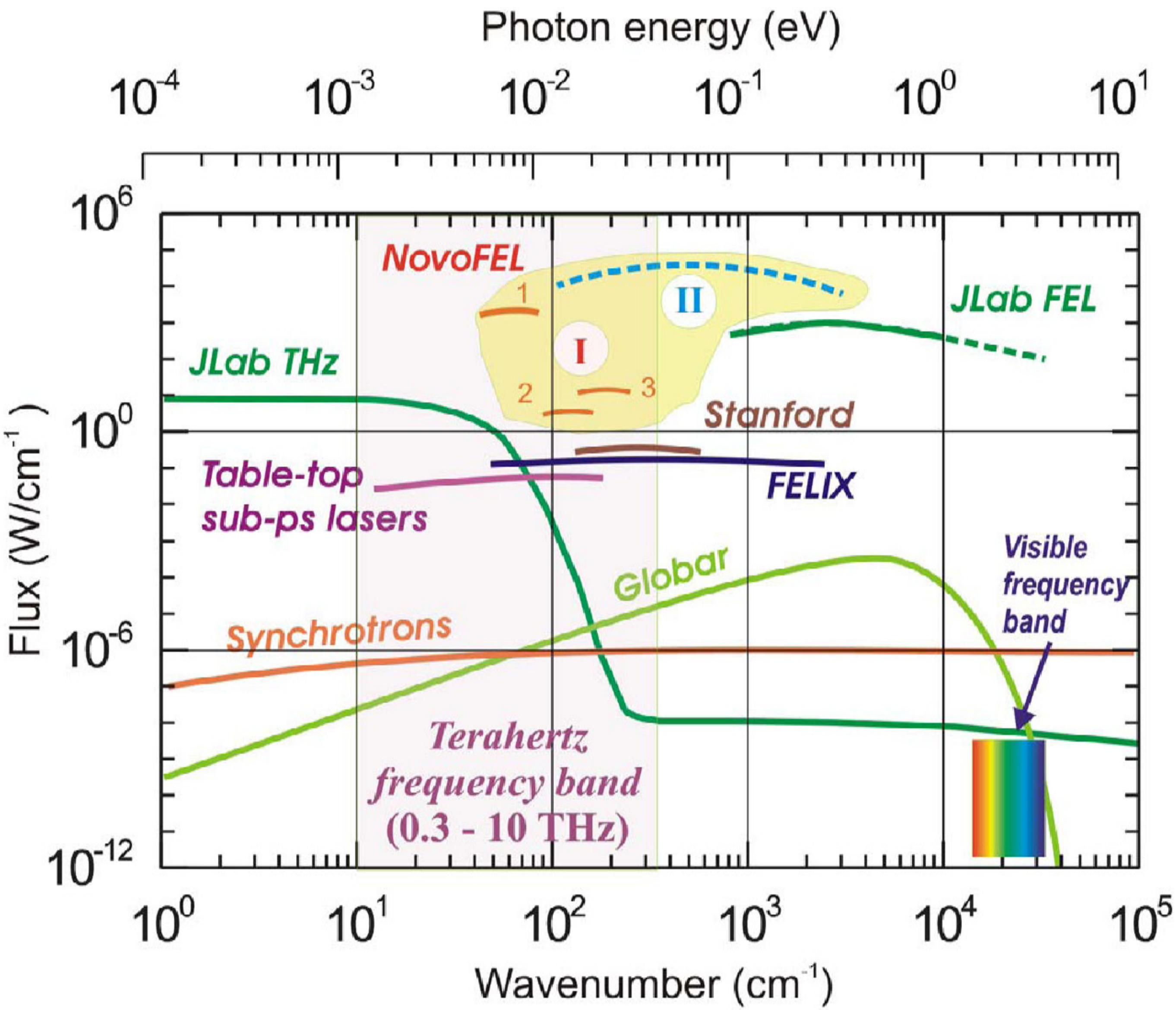
2 MeV injector



- Bunch repetition rate, MHz — up to 22.5
- Charge per bunch, nC — 1.5
- Start bunch length, ns — 1.5
- Final bunch length, ns — 0.12
- Final energy, MeV — 2

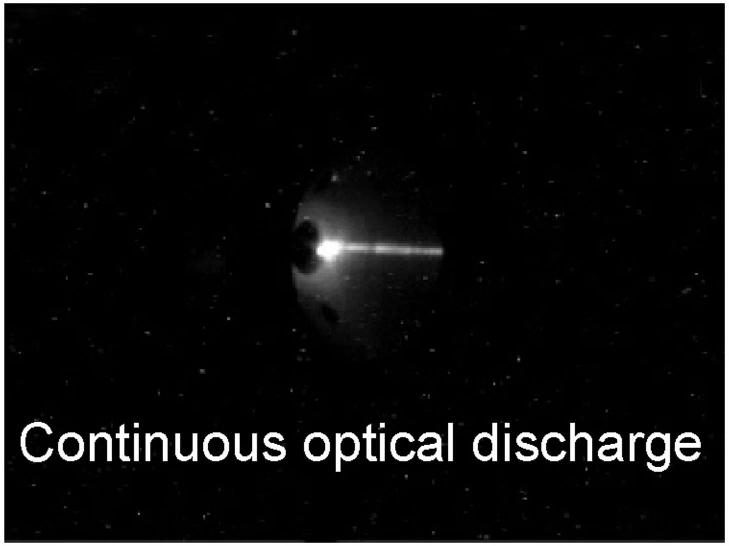
Courtesy N. Vinokurov

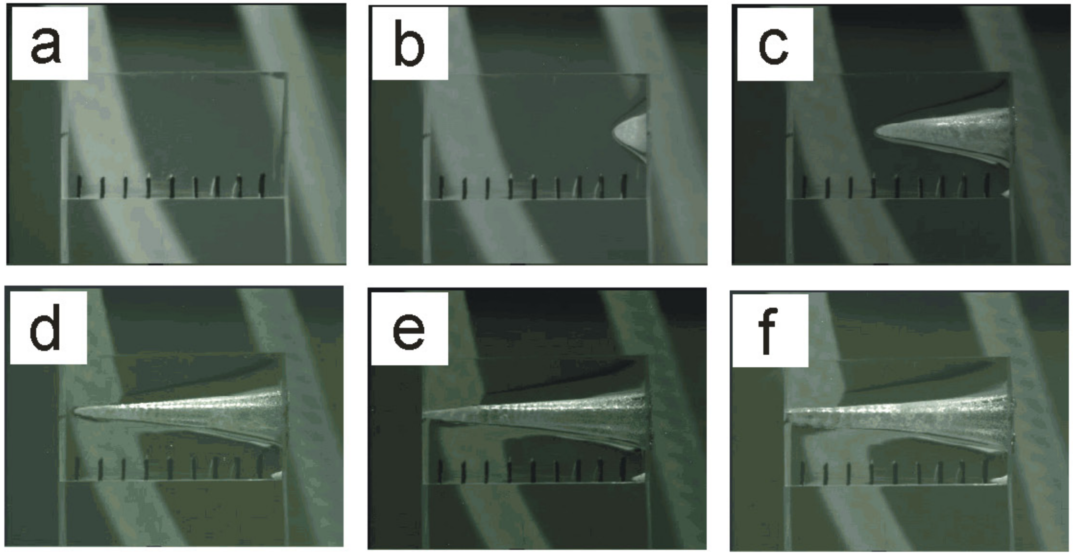
Radiation characteristics of THz sources



Courtesy N. Vinokurov

High average power of radiation (up to 400 W) in combination with high peak power (up to 1 MW) enables performing high power density experiments

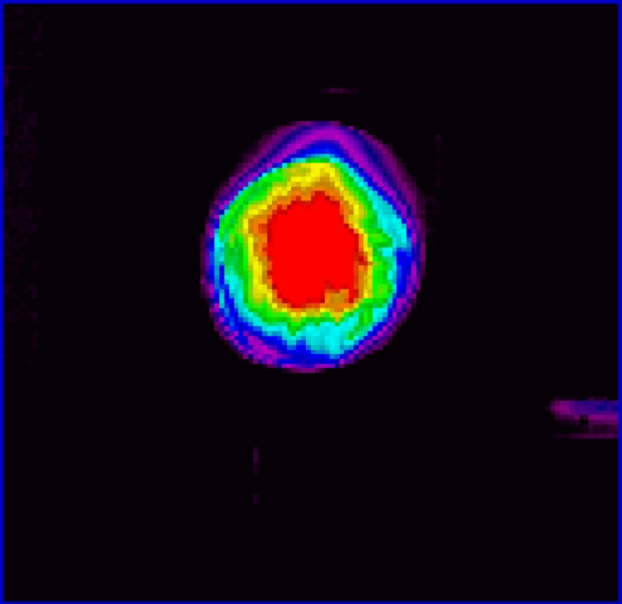




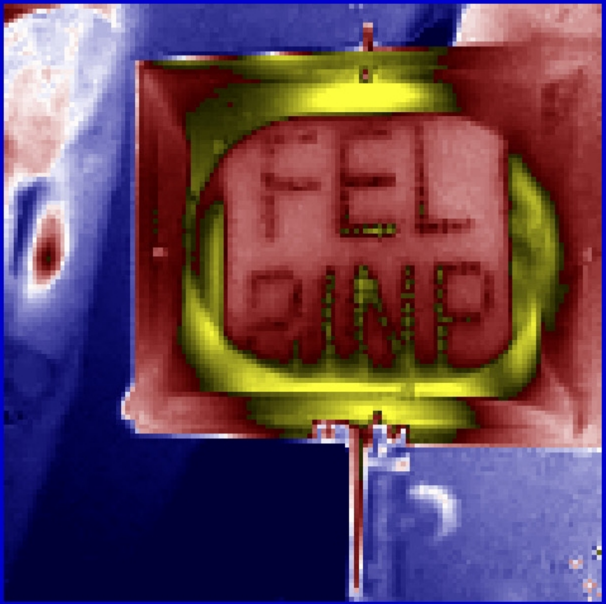
- Laser beam focused in the atmosphere with a parabolic mirror (f=1.0 cm) ignites a continuous optical discharge
- Unfocused laser beam drills an opening in 50-mm organic glass slab within three minutes (ablation without burning)
- These fenomena can be used for many fundamental and applied experiments (plasma physics, aerodynamics, chemistry, material processing and modification, biology…)

Courtesy N. Vinokurov

Recuperator FEL



Beam profile

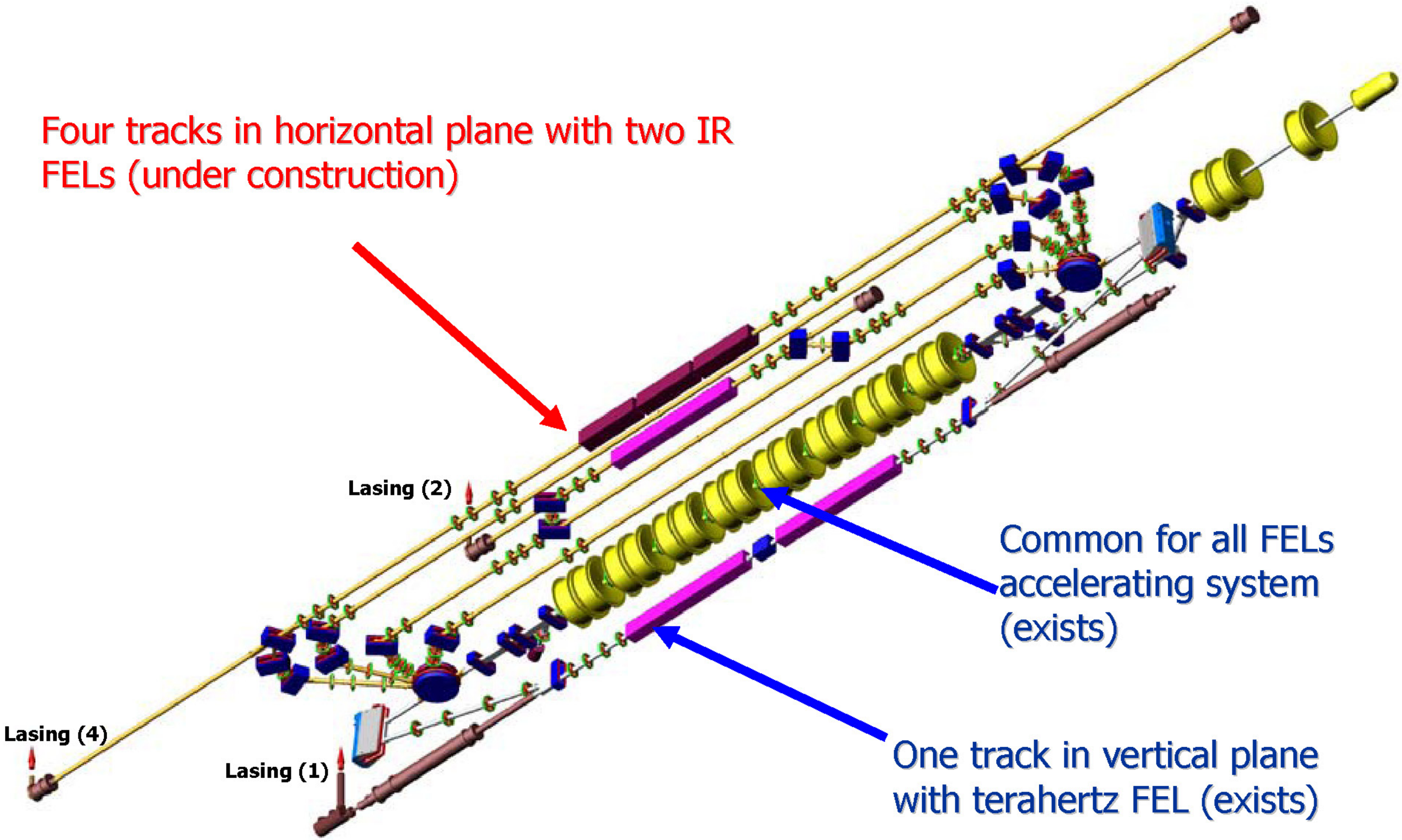


Metallic screen with holes

Keys inside paper envelope

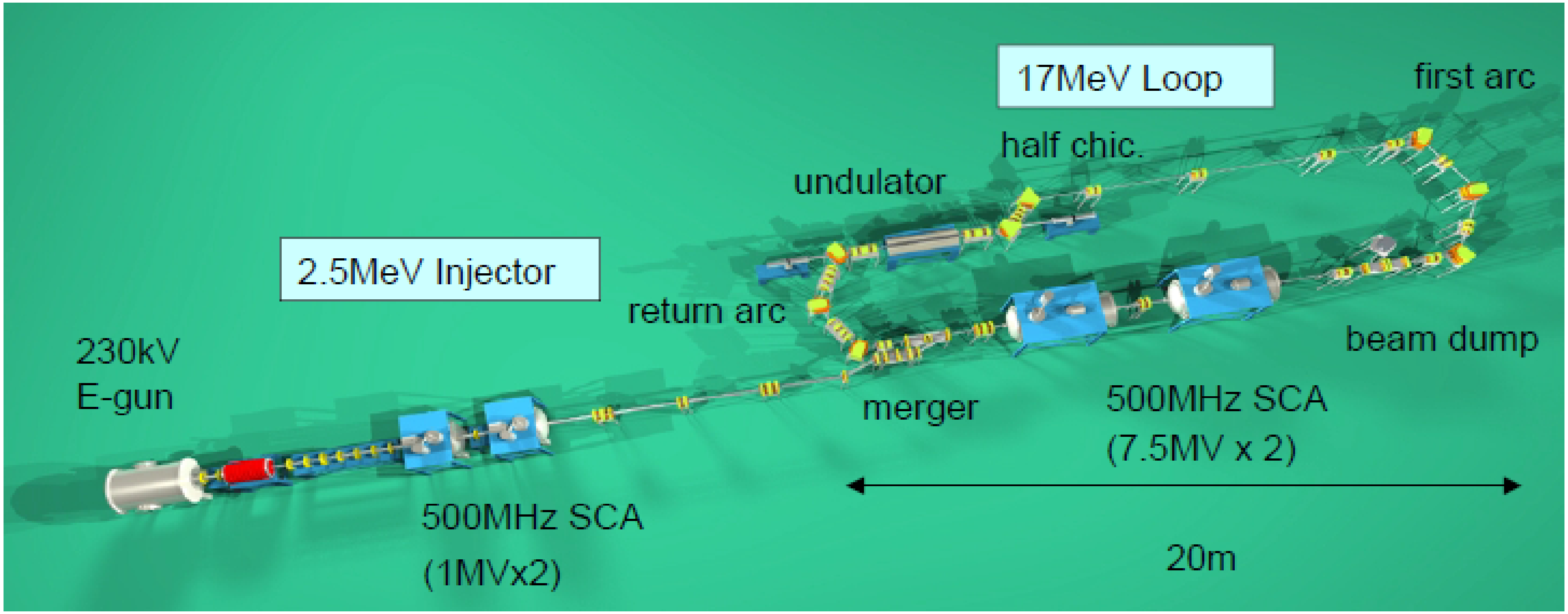
Budker Institute of Nuclear Physics **Courtesy N. Vinokurov**

Full scale Novosibirsk FEL (bottom view)



Courtesy N. Vinokurov

A high power ERL FEL at JAEA



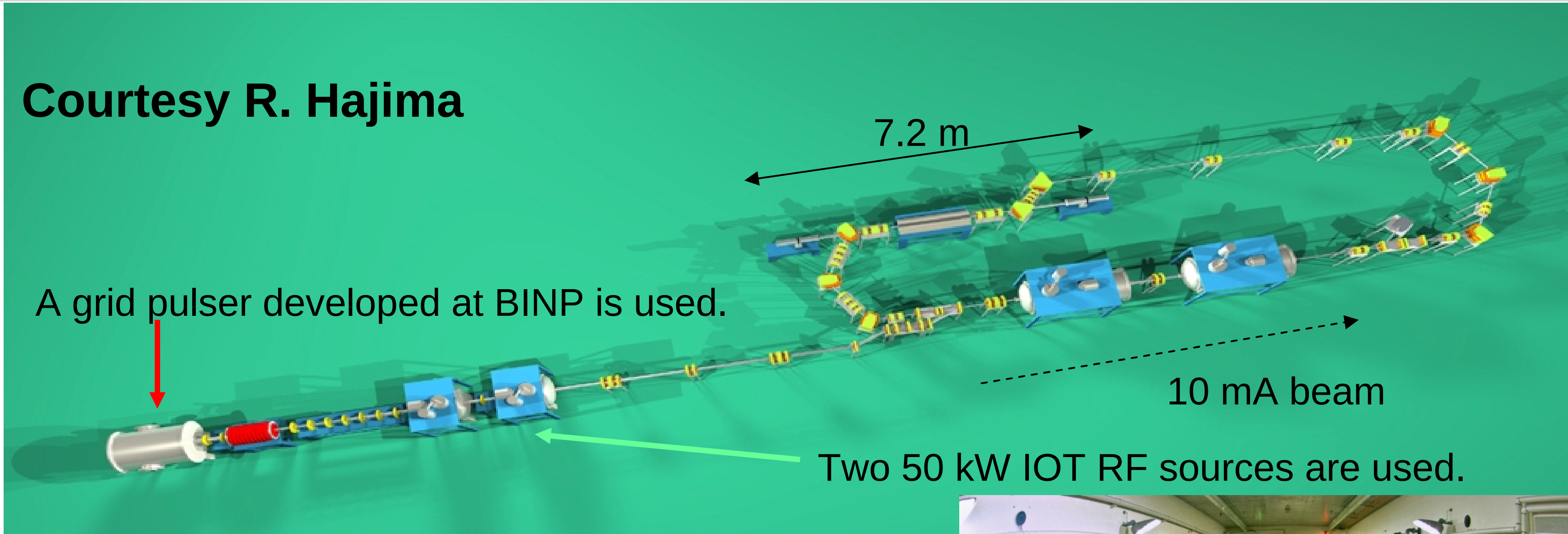
FEL wavelength is 22 μm and electron bunch carge is 0.5nC.

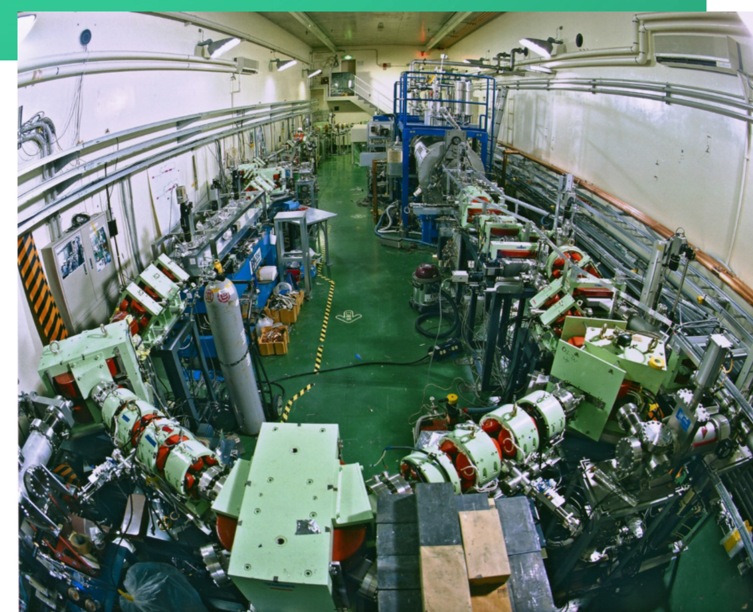
The injector consists of 230kV thermionic cathode DC gun, 83.3 MHz sub harmonic buncher and two single-cell 500 MHz SCAs.

17 MeV loop consists of a merger chicane, two five-cell 500 MHz SCAs, a triple-bend achromat arc, half-chicane, undulator, return-arc, and beam dump.

First lasing in August, 2002. R. Hajima et al., NIM A 507, 115 (2003).

JAEA ERL FEL





Energy = 17MeV
FEL : λ = 22μm
Bunch charge =400pC
Bunch length = 12ps (FWHM)
Bunch rep. = 20.8 MHz
Macro pulse = 0.23ms x 10Hz

JAEA ERL FEL

Proceedings of FEL 2006, BESSY, Berlin, Germany TUAAU

FEL OSCILLATION WITH A HIGH EXTRACTION EFFICIENCY AT JAEA ERL FEL

N. Nishimori*, R. Hajima, H. Iijima, N. Kikuzawa, E. Minehara, R. Nagai, T. Nishitani, M. Sawamura, JAEA, Ibaraki, Japan.

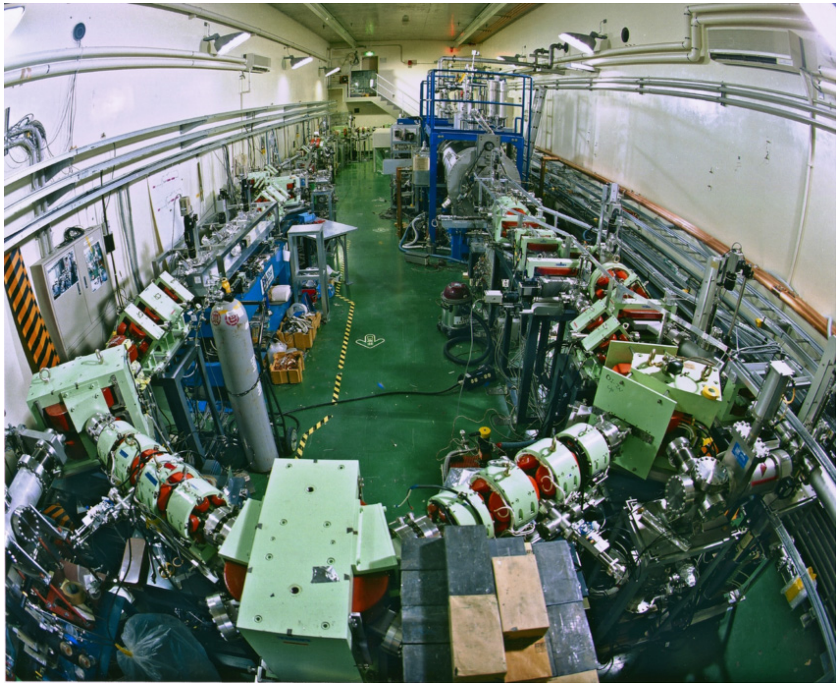


Table 1: JAEA ERL FEL parameters

Parameter	Measured
Beam energy at undulator	17 MeV
Average current at undulator	8 mA
Bunch charge at undulator	0.4 nC
Bunch length at undulator	12 ps (FWHM)
Peak current	35 A
Energy spread before undulator	1.5% (FWHM)
after undulator	> 15% (full)
Normalized emittance (rms)	40 mm mr
Bunch repetition	20.8250 MHz
Macropulse	1 ms $\times$ 10 Hz
Undulator period	3.3 cm
Number of undulator periods	52
Undulator parameter (rms)	0.7
Optical cavity length	7.2 m
Rayleigh range	1.00 m
Mirror radii	6 cm
Output wavelength	22 μm
FEL extraction efficiency	> 2.5%

Courtesy Hajima JAEA

JAEA ERL FEL

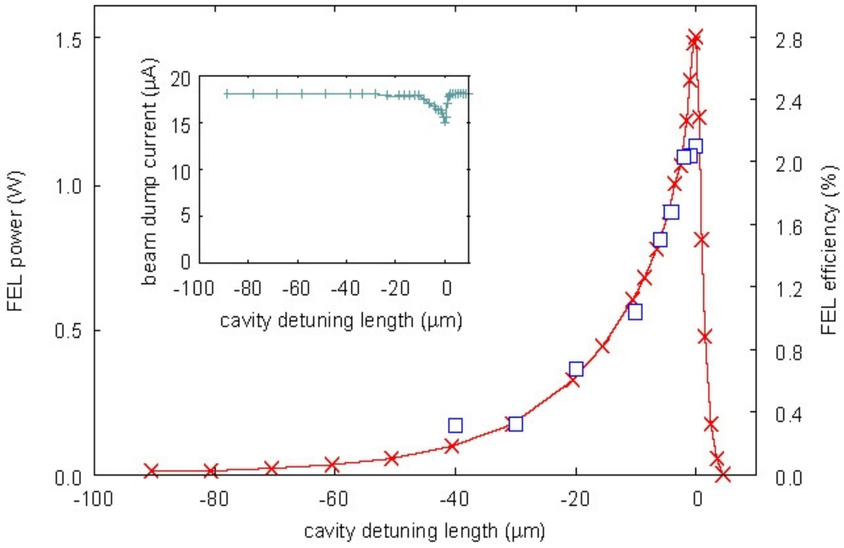


Figure 3: FEL power measured as a function of δL at macropulse length of 230 μs. FEL efficiencies obtained from the energy distributions of the exhausted electron beam are shown by open squares. The efficiencies near zero detuning length cannot be measured with our energy analyzer due to the limited energy acceptance, and they are determined from measured FEL power. The inset shows the beam dump current with respect to δL.

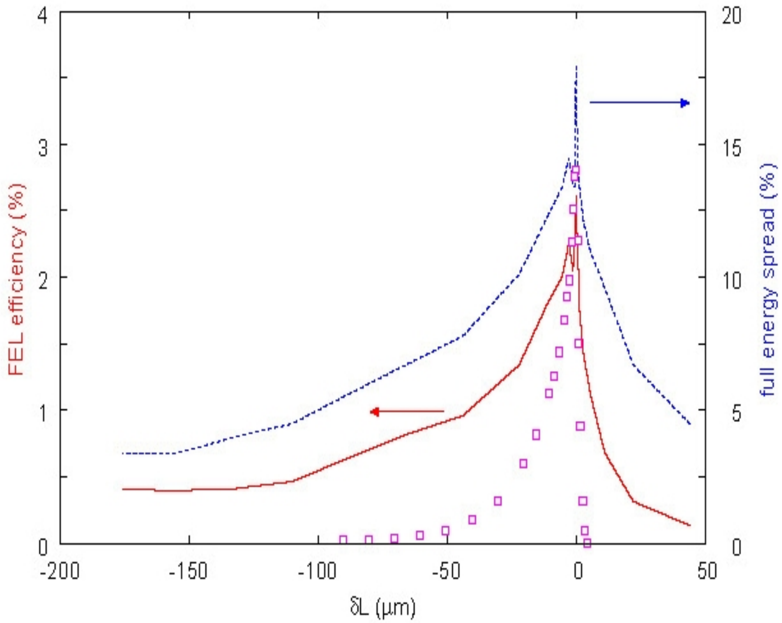
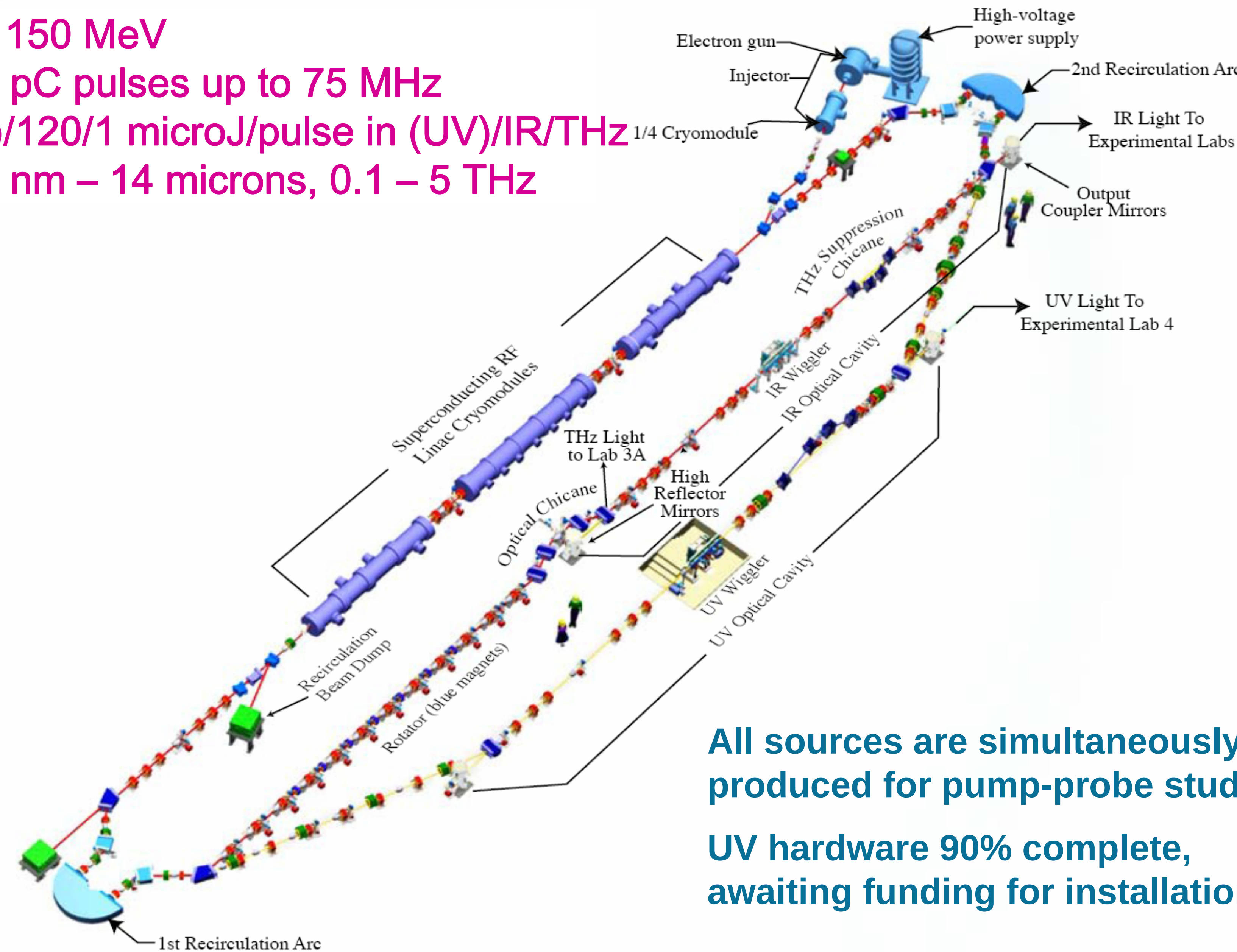


Figure 4: FEL efficiencies as a function of δL obtained from a one-dimensional time-dependent FEL simulation (solid line) and corresponding beam energy spread (dotted line). Measured FEL efficiencies are also plotted as open squares for comparison.

Courtesy Hajima JAEA

JLab Energy Recovered Linac

E = 150 MeV
135 pC pulses up to 75 MHz
(20)/120/1 microJ/pulse in (UV)/IR/THz
250 nm – 14 microns, 0.1 – 5 THz

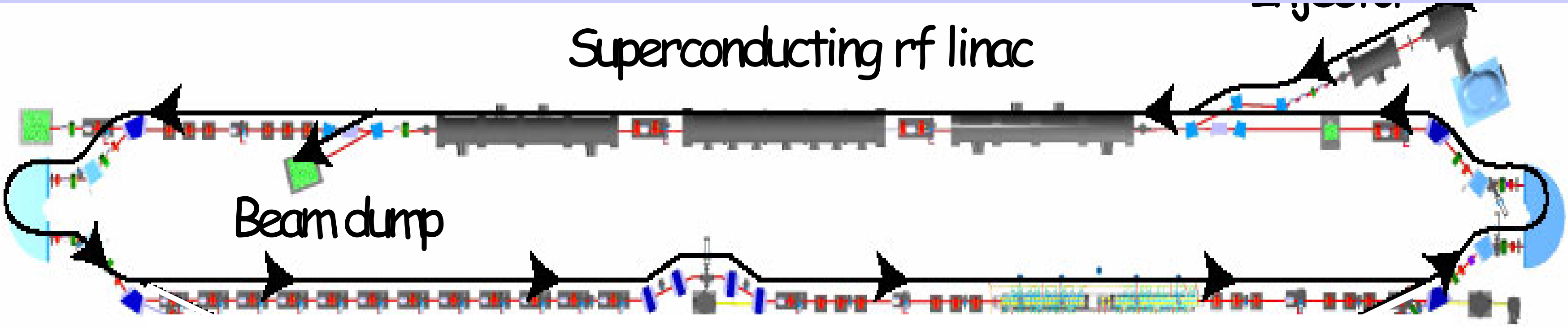


All sources are simultaneously produced for pump-probe studies

UV hardware 90% complete, awaiting funding for installation

The Jefferson Lab IR FEL Upgrade

Achieved 14.2 kW CW light power at 1.6 µm on October 30, 2006!

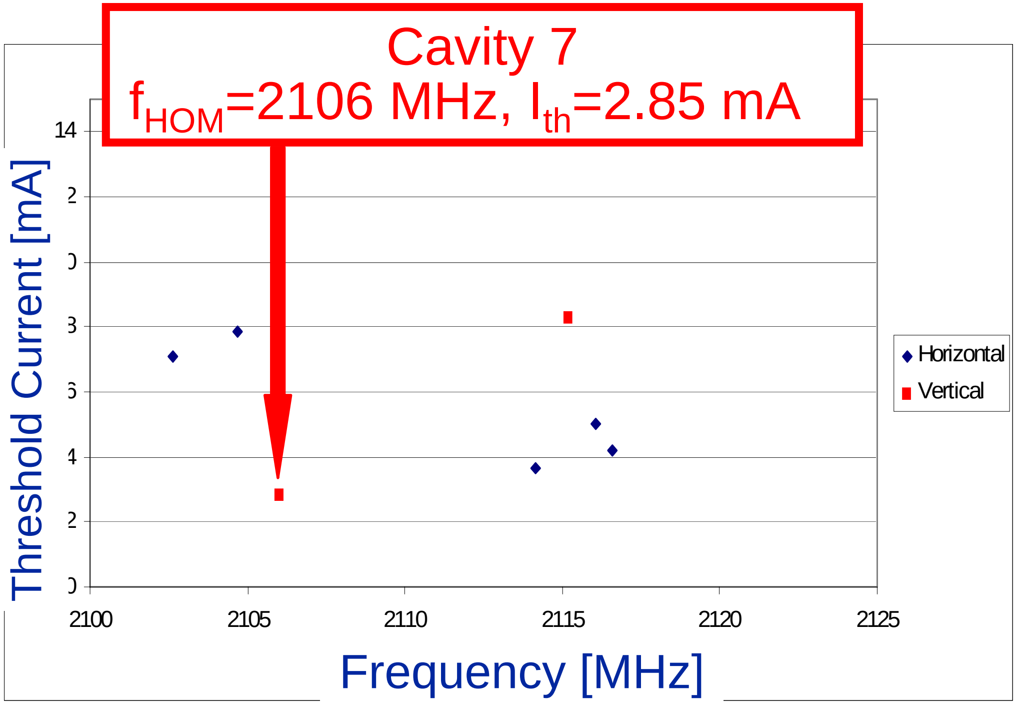


JLab IR FEL Electron Beam Parameters	Design	Achieved
Energy (MeV)	145	160
Bunch charge (pC)	135	270
Average current (mA)	10	9.1
Bunch length* (fs)	500	150
Norm. emittance* (mm-mrad)	30	7
Max. Bunch rep. rate (MHz)	74.85	74.85

*Quantities are rms

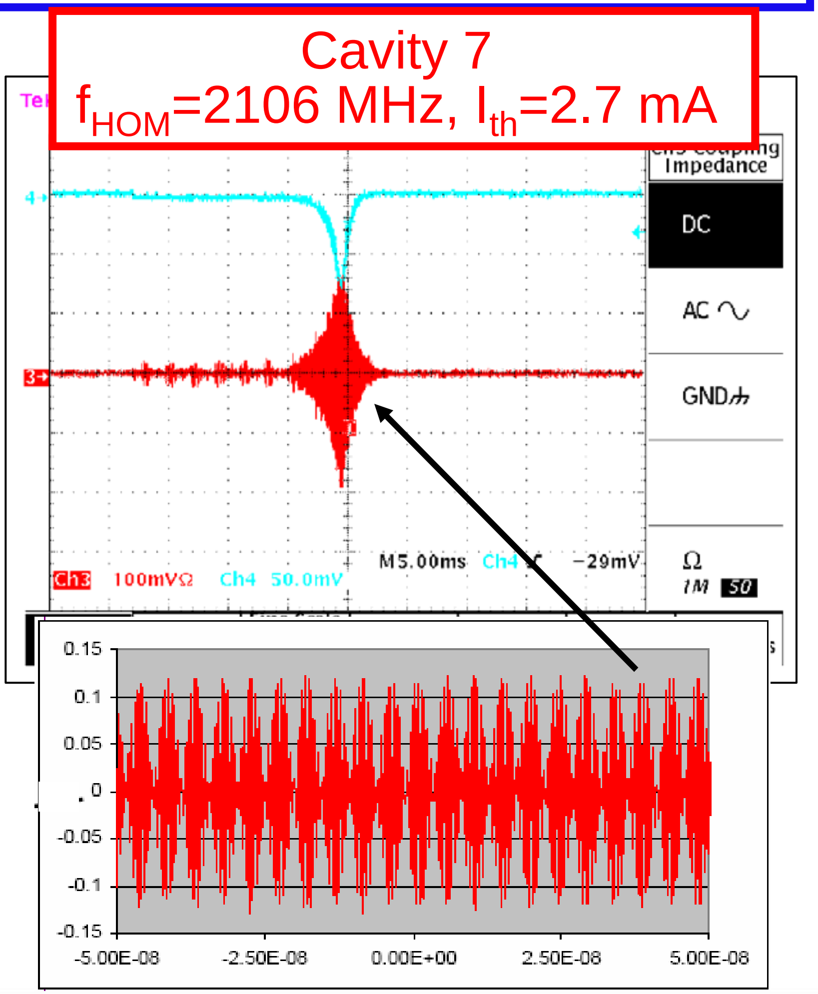
BBU Simulation and Observation

BBU simulations of the JLAB 10 kW FEL

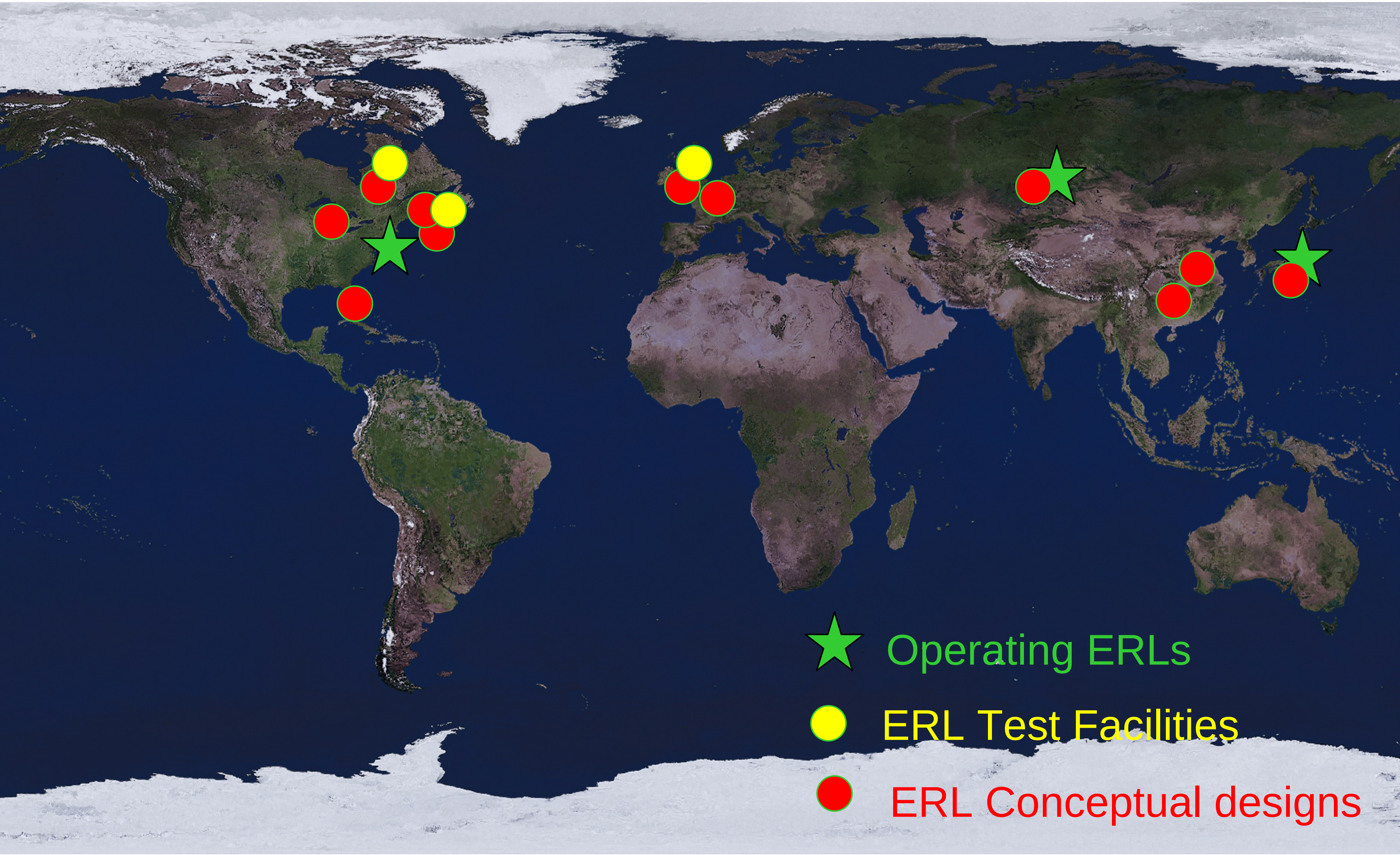


HOM data based on measurements
Model recirculation matrix

BBU observation in the JLAB 10 kW FEL

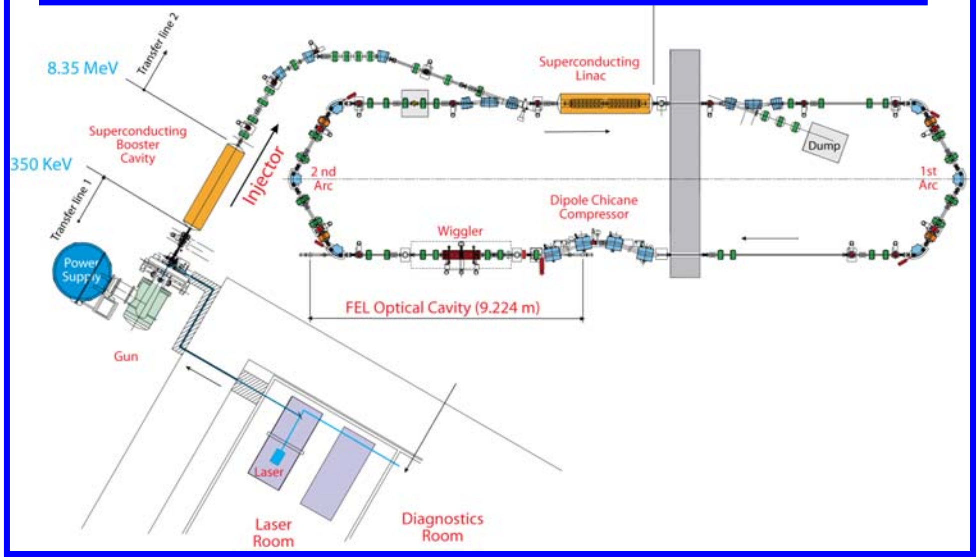


Operating and Future ERLs

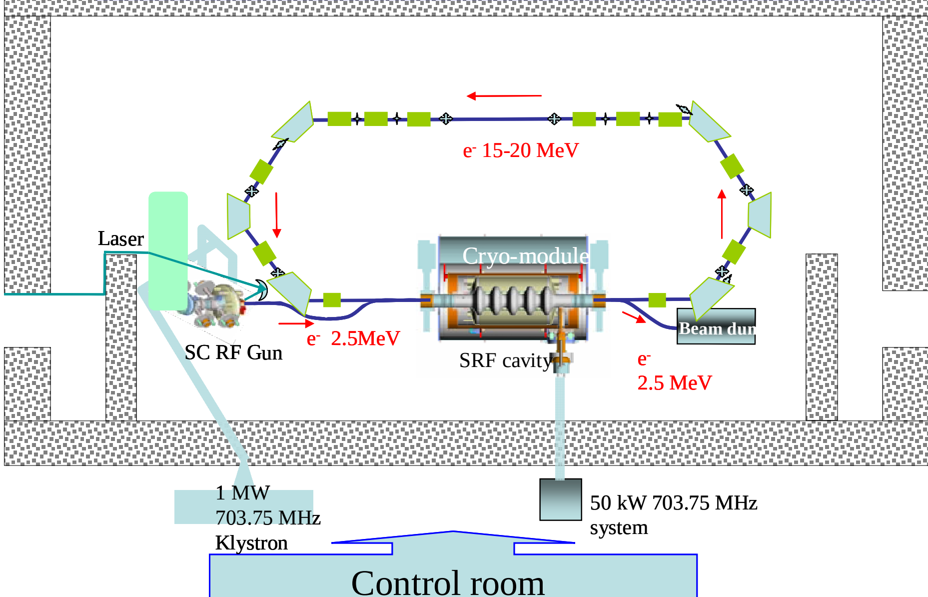


ERL Test Facilities in assembly and test

Daresbury ERL Prototype

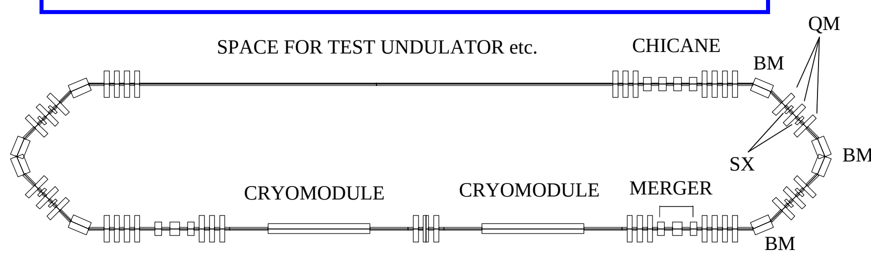


BNL R&D ERL



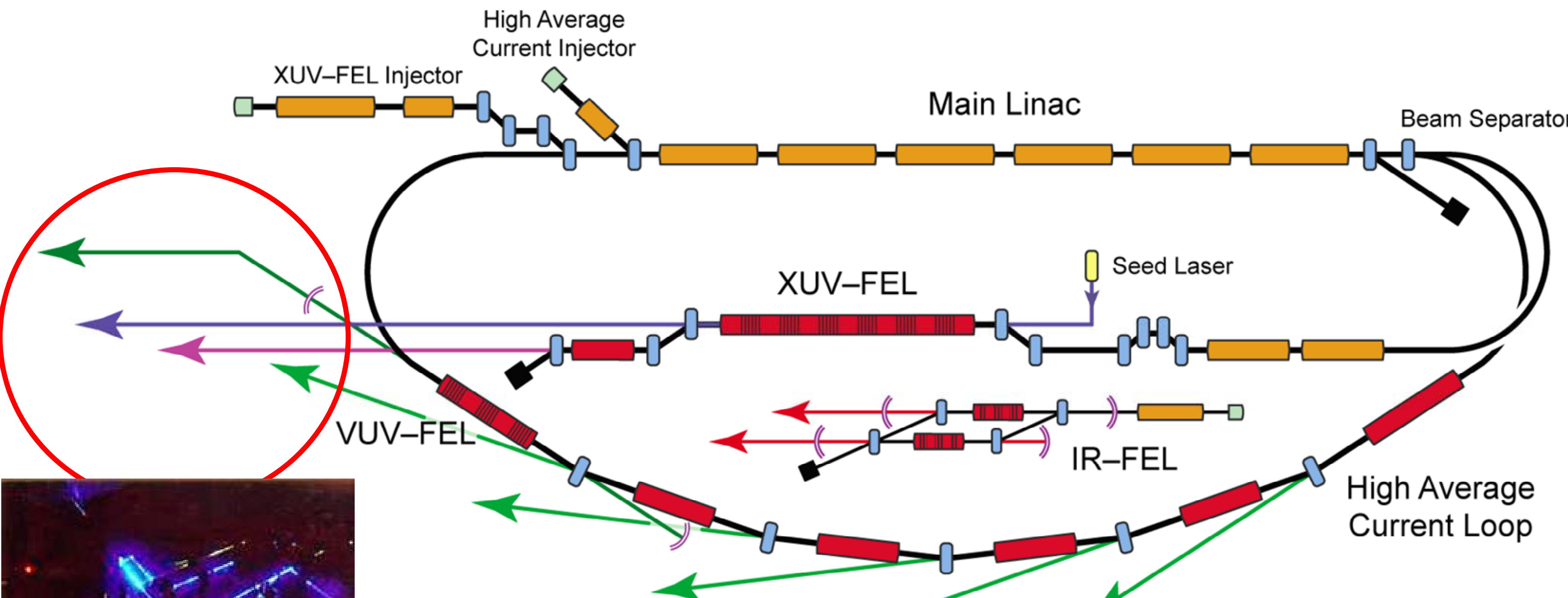
Cornell ERL Prototype Injector

Japan Test ERL



4GLS

Future ERL Light Sources: an example shows the possibilities

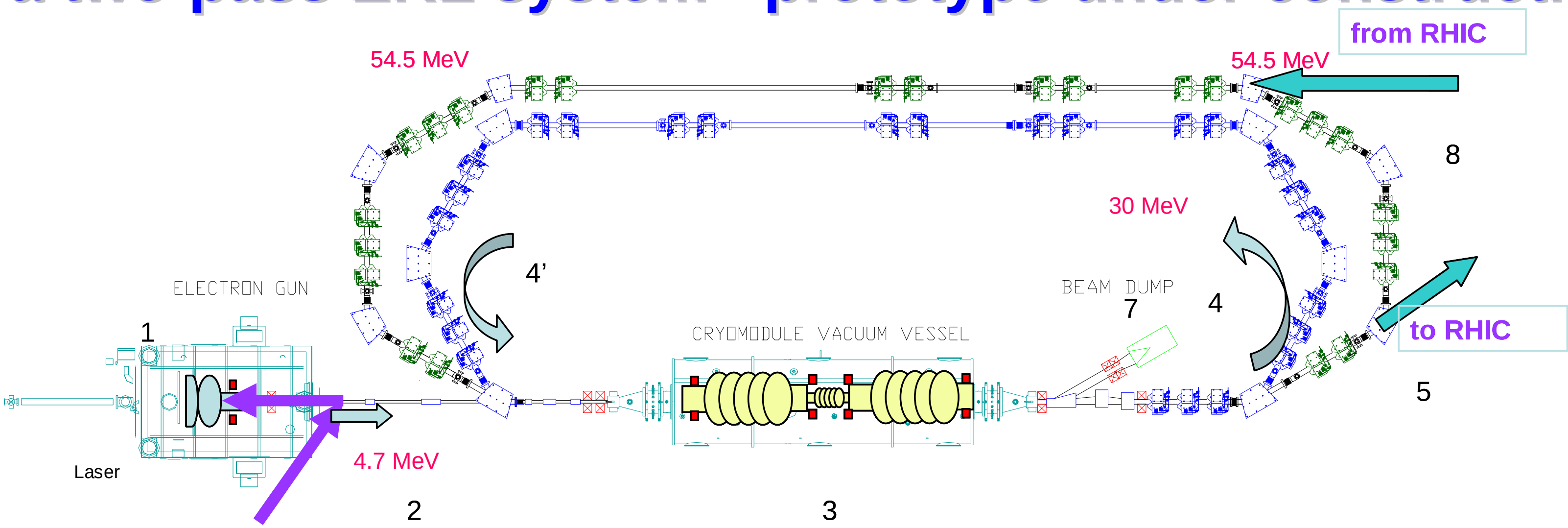


plus
laser sources

IR FEL Oscillator
VUV FEL Oscillator
XUV Amplifier
Spontaneous sources
All synchronized < psec

RHIC-II Electron Cooler

a two-pass ERL system - prototype under construction



Design Parameters

Courtesy BNL

Energy 54 MeV

Charge 5 nC/bunch

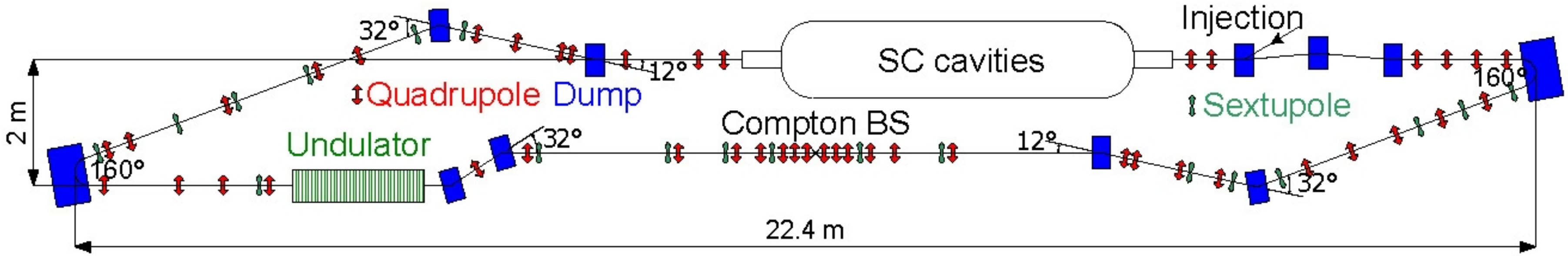
Emittance $\leq$ 4 mm-mrad

Average current ~ 50 mA

PAC07
WEOCKI03 Ben-Zvi

A PROJECT OF A HIGH-POWER FEL DRIVEN BY AN SC ERL AT KAERI

A.V.Bondarenko, S.V.Miginsky, Budker Institute of Nuclear Physics, Novosibirsk, Russia
B.C.Lee, S.H.Park, Y.U.Jeong, Y.H.Han, Korea Atomic Energy Research Institute, Daejeon, Korea



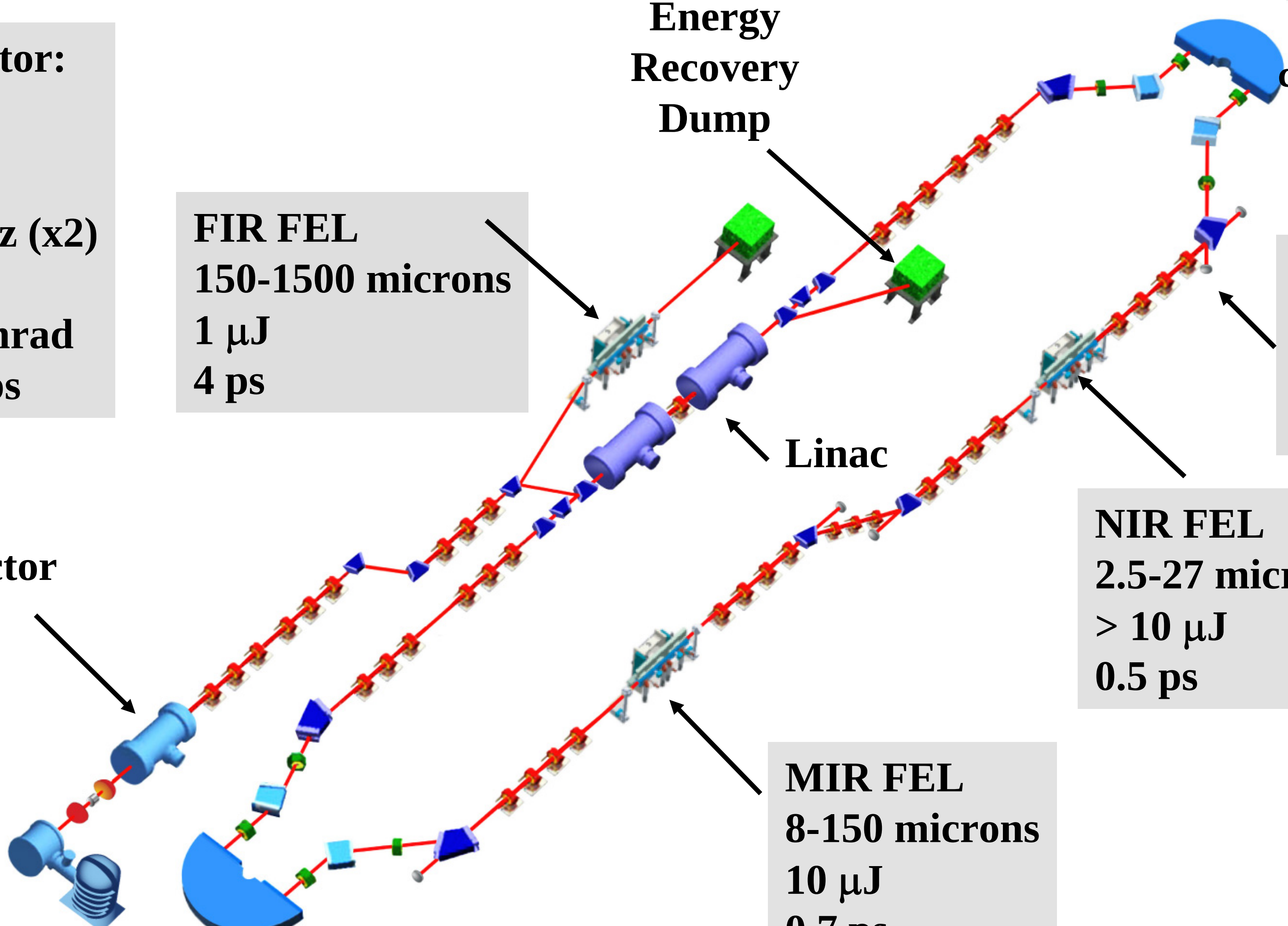
- bunch duration: 100 ps;
- number of electrons per bunch: 10^{10};
- electron energy (full): 10 MeV;
- repetition rate: 5.6 MHz;
- emittance: 2π mm·mrad;
- energy spread (relative): $6\cdot10^{-3}$.

FEL2007 MOPPH064

Big Light FEL for NHMFL

Accelerator:

60 MeV
3 mA
10.7 MHz (x2)
135 pC
10 mm mrad
80 keV-ps



Energy Recovery Dump

FIR FEL
150-1500 microns
1 μJ
4 ps

Linac

Injector

THz
Broadband
to 1 THz
1 μJ

NIR FEL
2.5-27 microns
> 10 μJ
0.5 ps

MIR FEL
8-150 microns
10 μJ
0.7 ps

Technology Development

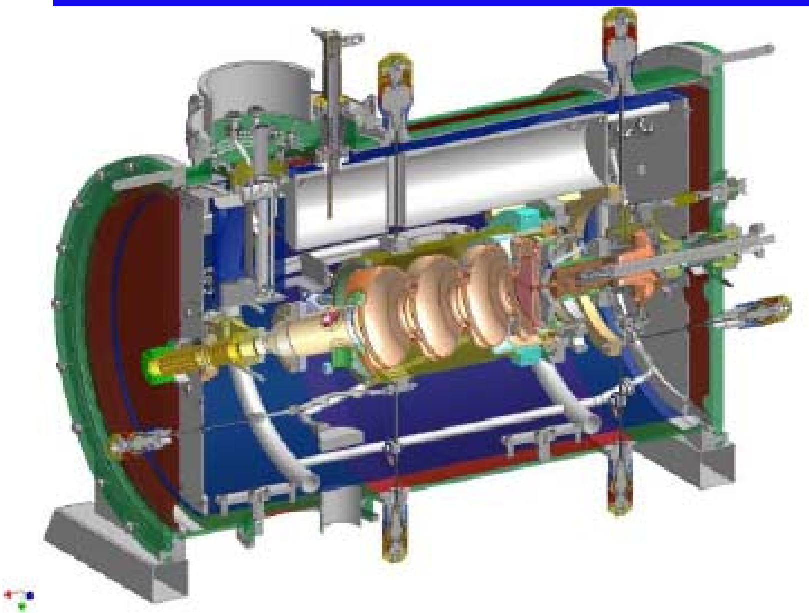
- Although other technologies are required the injector is key

- SRF
- DC

Goal: High brightness at high average current

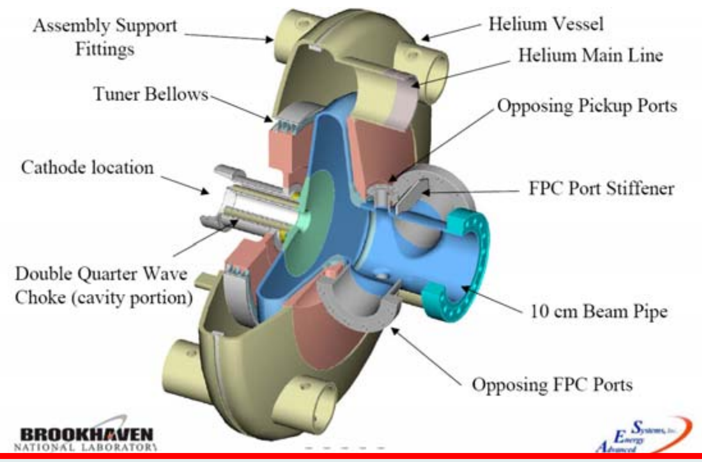
SRF photoinjectors

Rossendorf SRF gun

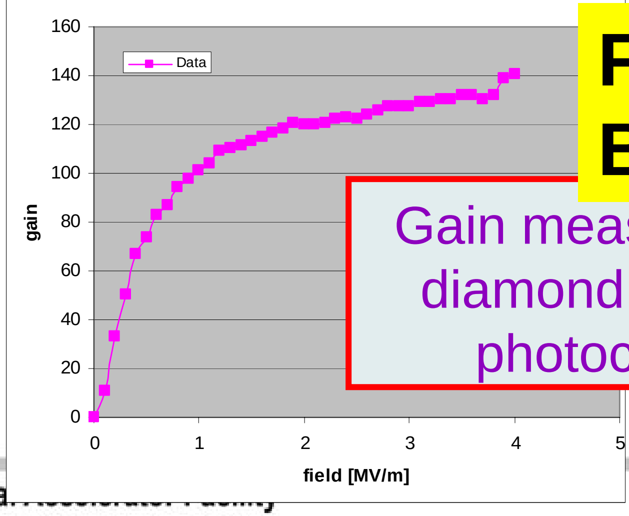


1.3 GHz, 9.5 MeV, CW
3 modes of operation:
- 77 pC at 13 MHz
- 1 nC up to 1 MHz (1 mA)
- 2.5nC at 1 kHz

BNL/AES SRF gun



703.75 MHz, 2.5 MeV, 500 mA,CW

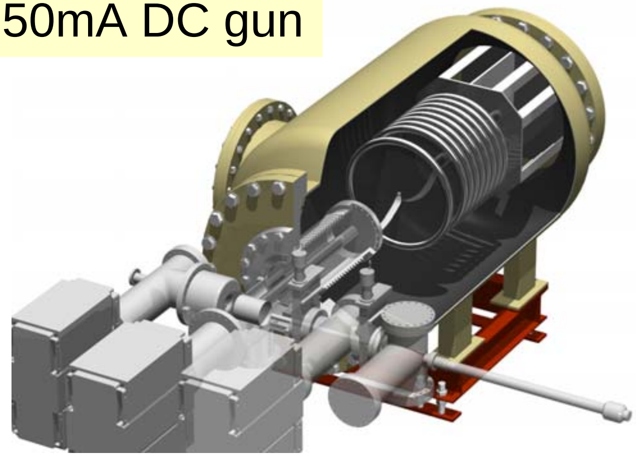


FEL2007 Ben-Zvi

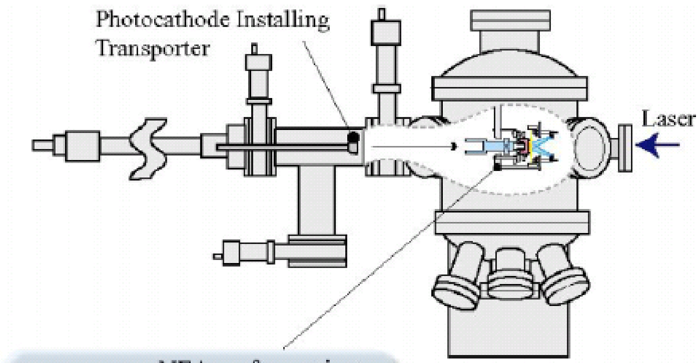
Gain measured from diamond amplified photocathode

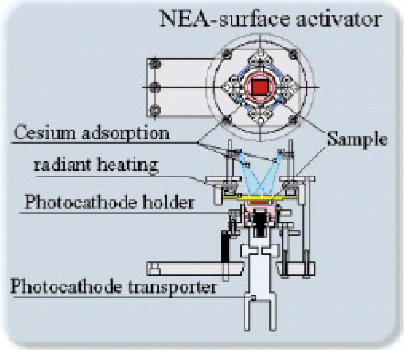
Development of a 250kV-50mA Gun

250kV-50mA DC gun



photocathode test bench





A DC gun for high-average current and small emittance is under development.

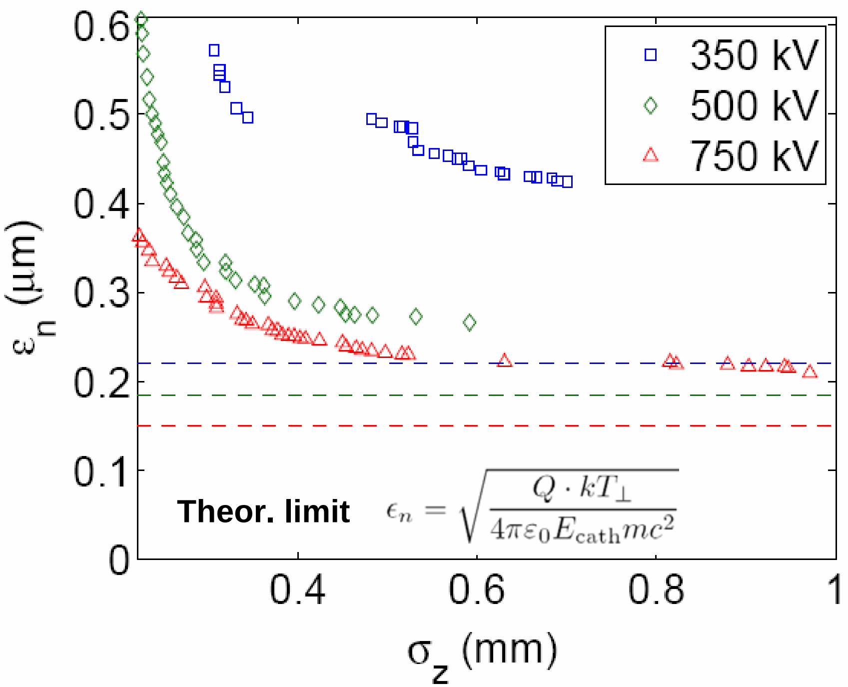
Basic studies on QE and life-time issues of NEA photo-cathode are in progress.

Courtesy: R. Hajima

Reaching ultimate emittance limit in a DC gun

Cornell ERL Prototype Injector

K-J Kim, FEL2007
1 Angstrom FEL Oscillator!



Multi-parameter optimization achieves 0.1 mm-mrad, 80 pC dominated by cathode temperature

Courtesy: I. Bazarov

Industrial applications

Does it make sense to use a high power FEL in an industrial setting?

It needs an application that works better/cheaper than any existing approach

It must be something that people are willing to pay enough for to make a profit over the costs

You have to be able to make and sell enough of the product to cover the economics

- *Need an FEL of sufficient power to make enough product to satisfy a market.*
- *FEL must be simple to operate, reliable, efficient,...*

Example Industrial applications

Nanotube production
Metal surface amorphization for corrosion resistance
Metal nitriding for hardness
PLD of metals
PLD of organics
Microengineering of components

Metal Amorphization

Process: FEL light produces amorphizes steel surface providing 3x improvement in corrosion resistance.

Technical status: process works at scientific level, we know the parameters for optimum output

Figure of merit: Need ~ 1J/cm^2 scanned over the metal surface. Short wavelengths are better but < 2 microns works.

Required to move forward: Need good scanner technology. Market analysis required to validate investment. Economics positive for high value targets such as turbine blades at < $0.01/kJ

Dangers: Must demonstrate to industry value added. Difficult scanning geometries are a problem. No industrial activity at present and present suppliers do little R&D.

Metal Nitriding

Process: FEL light is used to create nitride coatings on metal surfaces. Commercial plasma method requires vacuum to work. Competing laser methods don't produce the same quality coatings

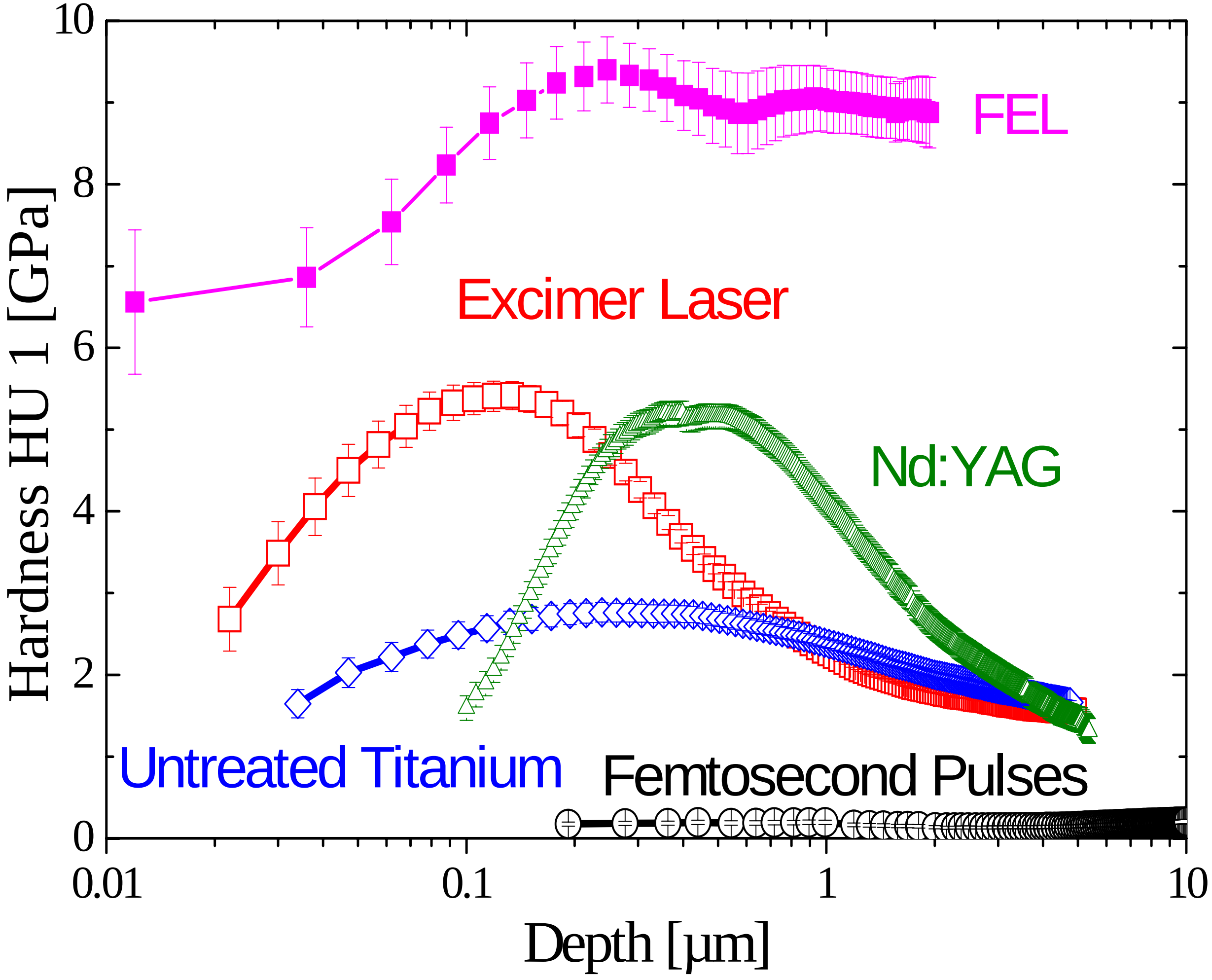
Technical status: A scientific demonstration of approach at JLab was a very successful initial step and produced several publications. Process optimization has not yet been done.

Figure of merit: Need ~ 0.1 to 1J/cm^2 scanned over the source material at short IR wavelength. We don't expect strong wavelength dependence but shorter is probably better.

Required to move forward: Need optimization of process parameters and demonstration of specific application. Market analysis required to validate investment. Economics unknown at present but there are likely high value coatings which provide an entry to market at < 1¢/kJ, maybe < 10¢/kJ

Dangers: Process parameters may be difficult to control. Must compete in existing market

TiN: hardness – comparison by laser



Femtoseconds – very soft (nanocluster)

FEL highest hardness and thickest coating (>5 µm)

P. Schaaf, Gottingen

E. Carpene, PS, *MRS Proc.* 780 (2003) Y5.8.1
E. Carpene, M. Shinn, PS, Appl.Phys. A (2005) i

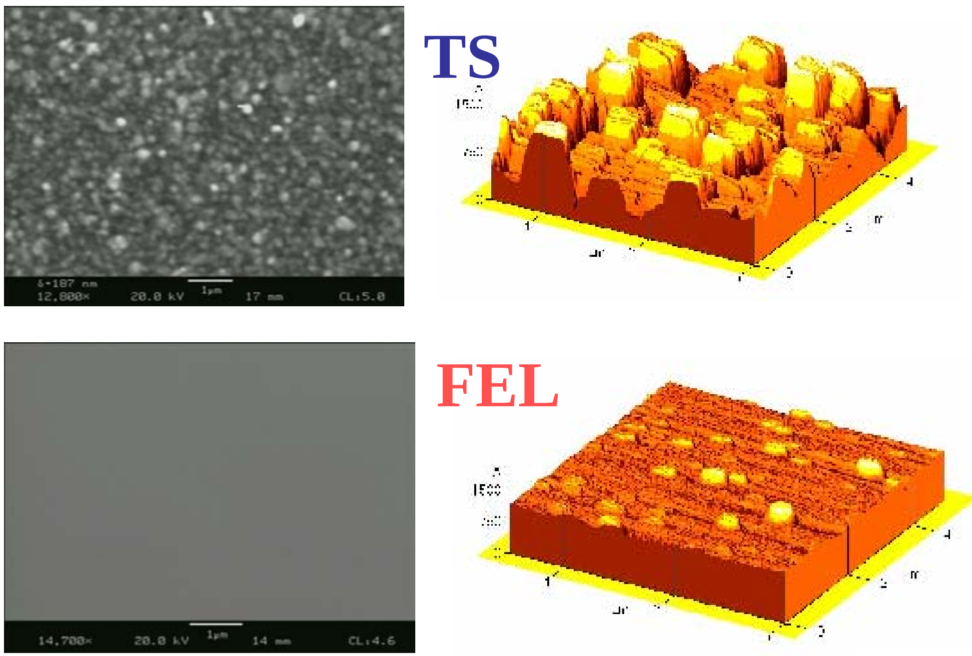
Benefits of short pulses and high rep. rate

Pulsed laser deposition with the JLab-FEL

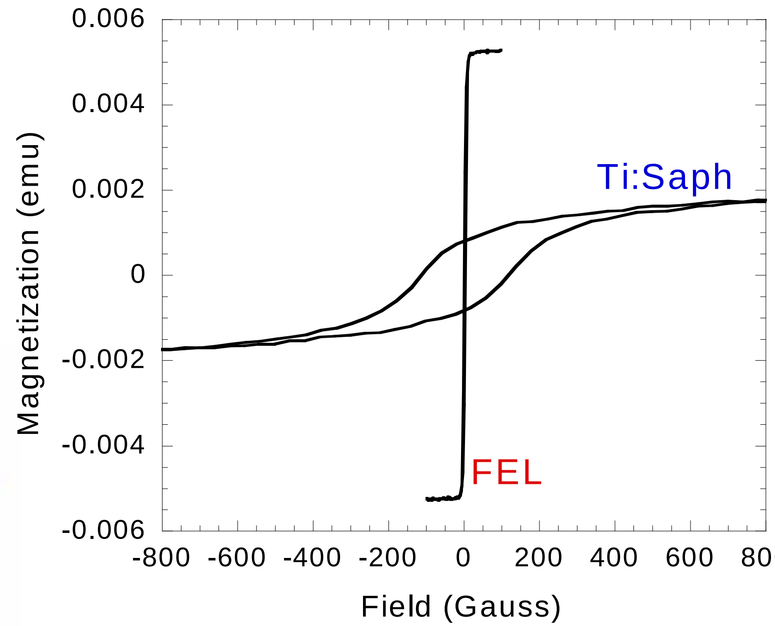
A. Reilly et al. CWM
J. Appl. Phys. 95 3098 (2003)

Deposition of metals with high rate (up to 200 Å/sec)

Particulate free films (< 1 cm^{-2}) of high quality compared to low repetition rate Amplified Ti:Sapphire deposition



SEM (left) and AFM (right) of NiFe films grown with an amplified Ti:Saph (top) and the FEL (bottom).



Magnetization of NiFe films grown with amplified Ti:Saph and FEL. Note high quality, low coercivity (~ 5 Gauss) of FEL film.

FEL Economics

What is cost of light production permissible to meet FEL economics?

10¢/kJ for low volume, high value added process: microengineering?

1¢/kJ for medium volume, modest value added process: PLD of magnetic coatings for hard disks?, nitriding? organics deposition?

0.1¢/kJ for high volume, low value added process: polymer surface amorphization?

n.b.: commercial excimers cost 50¢/kJ, solid state lasers 1-10¢/kJ , CO_2 lasers 0.1-0.5¢/kJ to run in an industrial setting

FEL Economics

How much product might you make? What can it cost?

Mid-Value production example:

An industrial system running at 10 kW for only 5000 hours/year produces 1.8×10^{11} Joules.

At 1 J/cm^2 this treats or covers 18 Mm^2

This process would have to charge $0.55/$m^2$ to sell $100M/yr. This is borderline profitable for some high value added processes

(Note: You pay $1/$yd^2$ at Carpet City for anti-stain treatment)

FEL Economics

What does it cost to build a high power FEL?

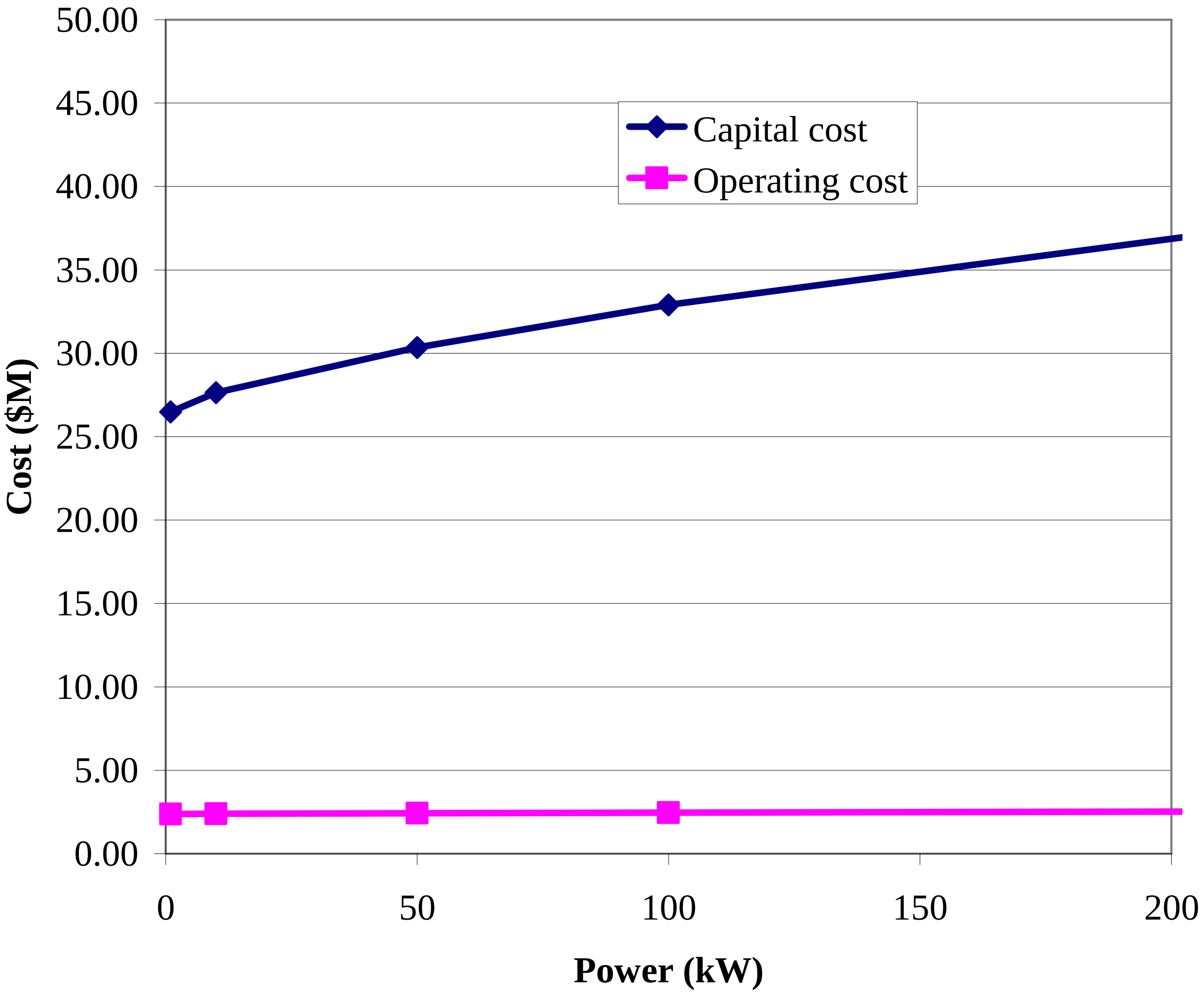
Analysis and experience at JLab indicate that 10x in power costs < 2x more

JLab and AES independently estimate first article 100 kW system at ~ $70M. The JLab IR Upgrade cost ~ $30M and has lots of bells and whistles undesirable in an industrial system

Latest research indicates reducing injection energy to as low as 5 MeV is possible; this is very helpful in reducing costs and improving wallplug efficiency. IOTs now under development also help with wallplug efficiency

For < $0.01/kJ delivered need 100 kW for $35M for multiple copies. We believe this is very achievable for IR, and not far off for UV.

Cost analysis shows weak dependence on power



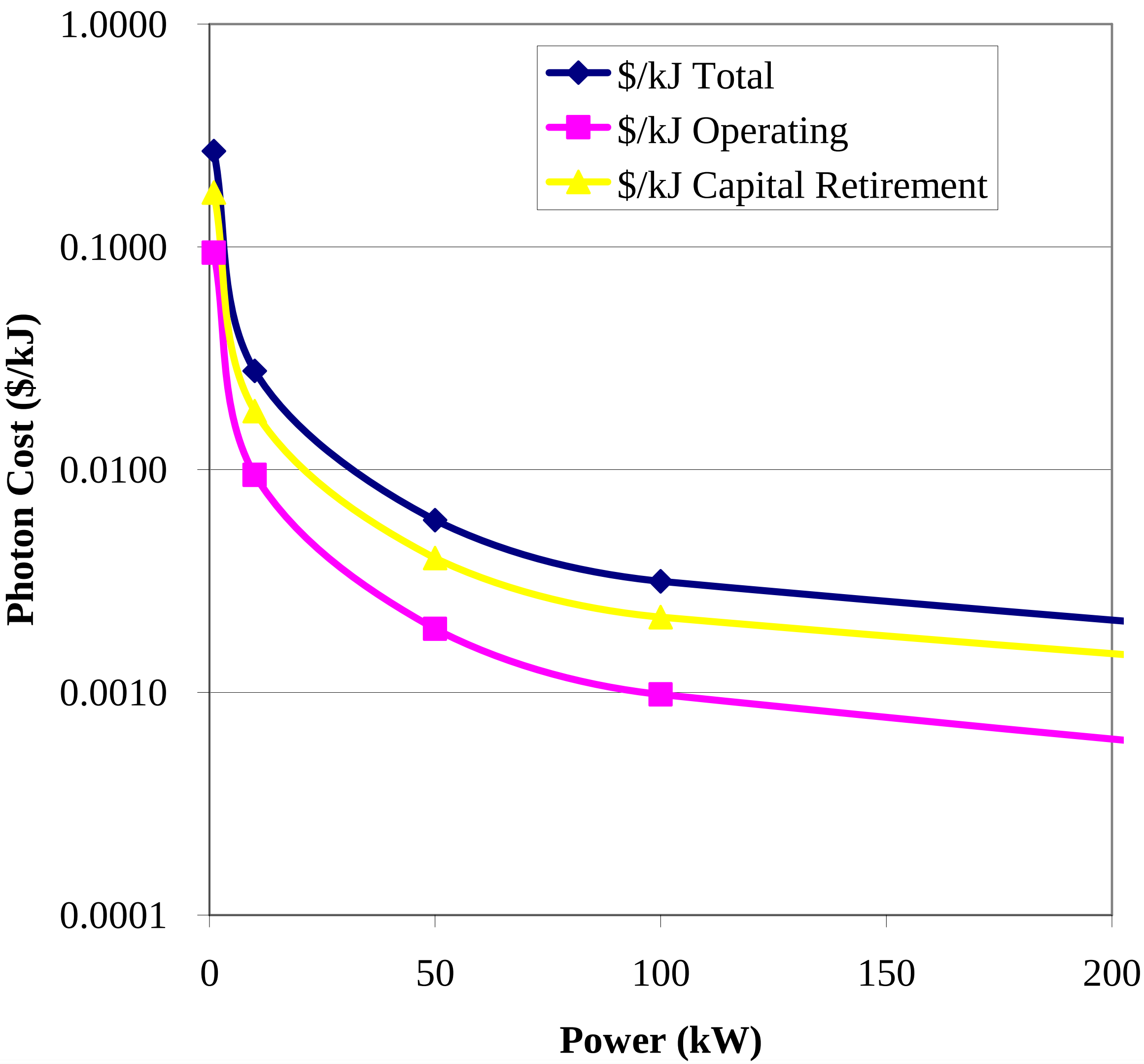
Capital cost:

- **No NRE, IR output.**
- **Add ~ $7500k for UV**

Operating cost:

- **Electric cost @ 0.08/kWH, 8000 hrs/yr**
- **6 year flat capital amortization**
- **Operators**
- **Maintenance contract**
- **Cryogens**
- **No material handling**

Estimated cost per photon meets requirements



Cost estimates appear to meet entry level goals of < 1¢/kJ at > 40 kW output

Summary

Lots of activity in ERL based FELs and related light sources

Much progress in achieving higher power

FELs are now at a technical maturity level where one can consider industrial applications requiring 10-100 kW

A number of potential applications have been identified and are under investigation; many others possible

FEL economics looks favorable for mid and high value added processes

We intend to carry forward these ideas and establish lab-industry partnerships to validate and commercialize these technologies in parallel with improving FEL performance

Summary

Lots of activity in ERL based FELs and related light sources

Much progress in achieving higher power

Still many challenges to keep researchers employed for many years!

Acknowledgements

Too many to get all of them!

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